An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques

Kayo Ide
Institute of Geophysics and Planetary &
Department of Atmospheric and Oceanic Sciences
UCLA, Los Angeles, CA 90095-1567
phone: (310)825-2970 fax: (310)206-3019 email: kayo@atmos.ucla.edu

http://www.atmos.ucla.edu/~kayo
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LONG-TERM GOAL

Much data in the ocean is Lagrangian in nature. Its full use in ocean prediction could advance significantly the Navy's ability both to predict ocean conditions and to assess the optimal strategies for deploying Lagrangian instruments and their associated sensors. The long-term objective of this project is the building of comprehensive and reliable DA platform for incorporating Lagrangian data into ocean state analysis and forecasting. By Lagrangian data, we mean both positions of moving instruments and also measurements taken by them. Autonomous vehicles (AUVs) that glide or maneuver in the ocean are new types of moving instruments, and they will be incorporated into the Lagrangian DA (LaDA) platform. This platform will be ideal for designing and performing the autonomous ocean sampling network, adaptive observations, and optimal deployment plans of such moving instruments. The new LaDA platform will form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data. By utilizing the Lagrangian data that have been underused in the past, the new platform is expected to enhance a naval predicted capacity.

OBJECTIVES

This project aims to develop an operational technology for assimilating Lagrangian data. Focuses are put on: 1) extension of our LaDA approach to develop a flexible platform, in which a variety of moving instruments that may not be viewed as Lagrangian in a conventional sense can be integrated; 2) design of observing systems to take full advantages of any moving instruments; 3) formulation of automated algorithms for optimal deployment strategies of the moving instruments to maximize the information content as observation and enhance predictive skill of the DA system; and 4) incorporation of dynamical systems theory to enhance predictive skill, in particular coherent structures and tracer fields. The extension will also have a capability to handle high-dimensionality and nonlinearity of the operational ocean models.

APPROACH

Our approach is to use the LaDA as a basis for the development of an operational technology that accommodates assimilation of data from a variety of measurements by any types of moving instruments, e.g., drifters, floats, and AUVs. Such a platform will be developed through a hierarchy of methods and models, as a balanced integration of DA techniques and dynamical systems concepts.

Recent developments in the theory and use of dynamical systems concepts for Lagrangian analysis will add a new dimension to the LaDA platform. Incorporating the geometrical approach will offer a much-needed template for observing system design for the LaDA platform. In return, accurate estimation and forecast of Eulerian flow field by assimilating such data will strengthen further the reliability of the observing system with moving instruments.

The LaDA is implemented using the Extended Kalman filter (EKF), ensemble Kalman filter (EnKF), and particle filter (PF). In operational applications, the EnKF is the most promising technique at the present time. The EKF and PF are, in contrast, useful for providing the insight into the DA problems and helping develop the basic concepts for sophisticated schemes of the observing system design in an operational environment.

Tests of our approach will be performed using the models with a variety of complexity, ranging form highly-idealized point-vortex systems, through intermediate shallow-water model wit a basin-scale box configuration, to the realistic model configuration for the Gulf of Mexico (GoM). The highly idealized models are used for the applications of the EKF and PF methods to gain and address fundamental issues associated with the LaDA. For operational applications, the EnKF is implemented in the GoM model. Issues associated with the EnKF and the LaDA are carefully addressed in the GoM application by incorporating the understanding gained from applications of the EKF and the PF methods in the simpler models.

Ideas from dynamical systems theory will be employed in every stage to provide a solid, mathematical template and foundation while casting conceptual simplicity on the complex platform.

WORK COMPLETED

Progress is being made in advancing LaDA towards operational use. This is being achieved through a coordinated effort to test and adjust the LaDA methods together with designs and tests of optimal deployment strategies through the hierarchical approach.

Issues essential to the LaDA have been investigated further. For practical reasons, the LaDA systems used either the EKF or the EnKF method in that past. Because both methods parameterize the background probability density by the error covariance, the LaDA system may experience occurrence of the filter divergence especially when the assimilation time interval is longer than the Lagrangian time scale of the drifters. This issue is investigated using several variation of the PF schemes that take the full background probability distribution into account have been developed.

For the estimation of the three-dimensional ocean evolving in time, a two-layer, point-vortex model were used to study how effectively the surface (horizontal) information from the Lagrangian observation propagates vertically to the layer below. The EKF and EnKF methods were used in this study.

The single-layer shallow-water model with a basin-scale box configuration was extended to the three-layer model. This model will be used to 1) investigate the effectiveness of the vertical propagation of observed surface information into layers below, and 2) advance the optimal deployment strategies for the drifters.

To achieve high computational efficiency towards the operational use, a LaDA system using the EnKF was implemented in a 4160-processor Dell Linux cluster at the University of North Carolina. This LaDA system currently uses a three-layer shallow-water moodel with the GoM configuration.

Issues associated with the EnKF method and the LaDA are being investigated in the GoM application through a series of the so-called "identical-twin experiments". Efficacy of the Lagrangian observation in the estimating the loop-current eddy was demonstrated against the Eulerian observations. Preliminary tests for the design of the deployment strategy were conducted.

A three-dimensional variational DA scheme for the regional ocean modeling system (ROMS) has been advanced further. This effort is lead by Yi Chao at Jet Propulsion Laboratory/California Institute of Technology.

RESULTS

While the standard KF outperforms the standard PF most of the time, the KF may fail when the conditions required for a robust DA system are violated, e.g., when the assimilation time interval is too long (Table 1). The PFs with the backtracking capacity not only overcome this problem completely but also outperform the standard KF and standard PF constantly. In particular, the PF with the directed backtracking shows excellent improvement over the standard KF.

Table 1. Comparison of the failure rate (%) for the KF method and three PF schemes. [Initial condition of the drifter at (1,-0.6) corresponds to the case where the data assimilation interval is too long for the KF. PF1 is the standard PF, PF2 is PF1 with stochastic backtracking, and PF3 is PF1 with deterministic backtracking. An experiment is called the "failure" if error of any vortices and drifter exceeds 1 at any time during [0,60].]

		Initial Condition of the Drifter			
		(0.3,0.6)	(1. -0.6)	(1, -1)	(2.4, -2.4)
Method	KF	8.8	81.4	2.6	9.6
	PF1	9.8	2.8	6.2	10.2
	PF2	1.4	0.2	0.2	7.6
	PF3	0.0	0.2	0.2	5.2

A series of the identical twin experiments showed that the LaDA works effectively using a realistic GoM system with a small number of driter observations (Figure.1). The control run (right column) was used to create the synthetic observations that were subsequently assimilated using the EnKF. As little as two drifters are needed for the LaDA to estimate the 'missing eddy' if the drifters were deployed according to judiciously chosen locations.

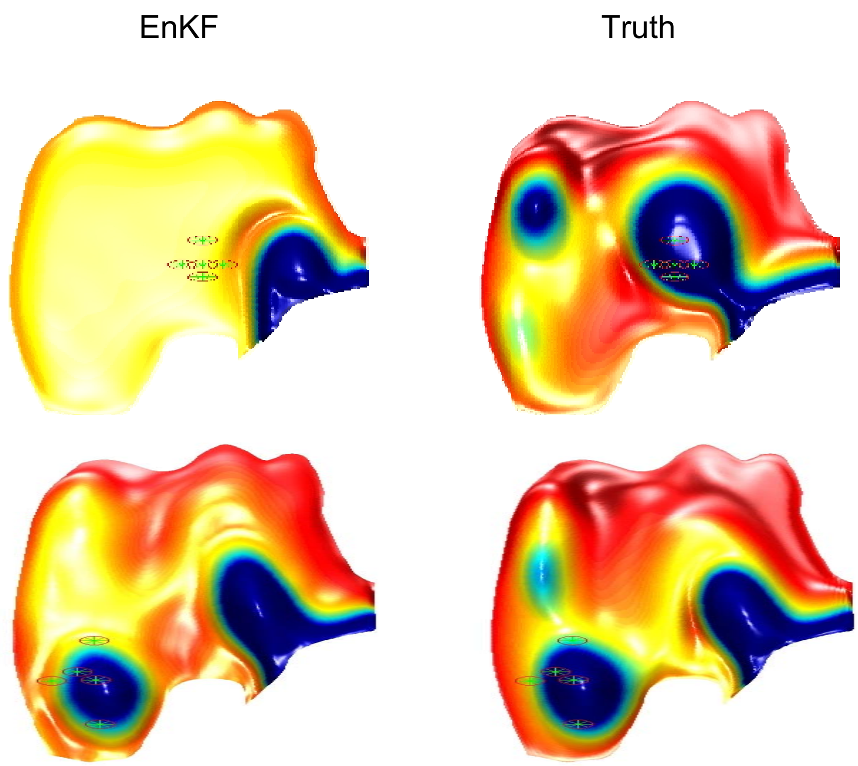

Figure 1. An identical twin experiment for the GOM using 5 drifters and 1280 ensemble members. [The "truth" (right column) and the corresponding "EnKF" analysis (left column), at starting time t_0 (top rows) and finish time t_0+T after T=100 days (bottom rows). Top-layer depth is shown in color. Blue and red correspond to high and low values of the top-layer depth, respectively. At time t_0, the five drifters deployed into the eddy in the "truth" whose trajectories are assimilated in the "EnKF". The "EnKF" starts from completely different initial condition (top left) from the "truth" (top right) at time t_0. By assimilating the 5 drifter positions every 6hrs, the "EnKF" gets closer and closer to the "truth". At time t_0+T, the "EnKF" (bottom left) successfully generates the eddy at the right location as in the "truth" (bottom right). Without DA, the GoM will undergo totally different dynamics from the dynamics of the "truth'; in particular, there will be no eddy in the GoM.]

The remarkable efficiency of the LaDA can be explained by considering the volume of influence, which is defined as the region in the ocean that will be affected by assimilating the data in question. The volueme of influence for the Lagrangian data is much larger than that for the Eulerian data (Figure 2).

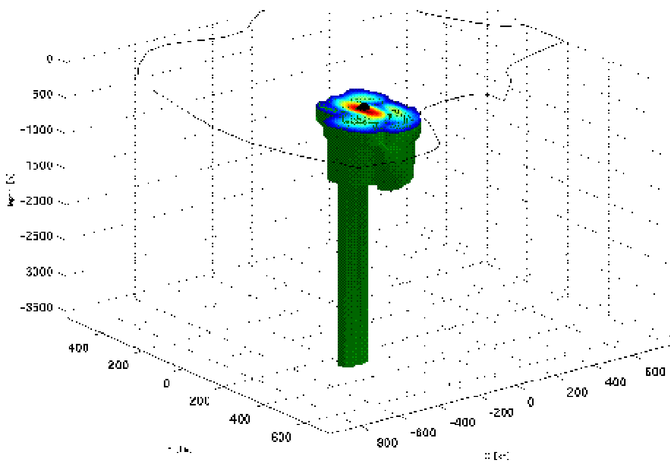

Figure 2: Volume of influence of 1 drifter.
[The black dot represents the location of the drifter. The green surface is the boundary of the volume. The colors are the maximum absolute correlation between the state and the observed location of the drifter.]

IMPACT/APPLICATION

With the excellent efficacy proven by this project, the LaDA is a promising technology for ocean DA in the opertaional use.

Realistic application of the LaDA using the GOM confirms the importance of drifter deployment location in the DA performance. Thus, the flow-template approach, through the application of dynamical systems ideas, offers a propitious potential to the effective design of the optimal drifter deployment strategies for the operationa use.

RELATED PROJECTS

1– NSF CMG Heavy Tailed Distributions in Geophysical flow: Physical Mechanisms and DA, in collaboration with Richard McLaughlin, Roberto Camassa and Christopher K.R.T. Jones (UNC-CH) and Didier Sornette (UCLA).

PUBLICATIONS

Chin, T.M., K. Ide, C.K.R.T. Jones, L. Kuznetsov and A. Mariano, 2007: Dynamic Consistency and Lagrangian Data in Oceanography: Mapping, Assimilation, and Optimization Schemes, Chapter 7, *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics* (eds. A. Griffa, A. D. Kirwan, A. J. Mariano, T. Özgökmen, and T. Rossby), Cambridge University Press

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